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Morphological Effects of ArF Excimer Laser Irradiation on Enamel and Dentin

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Background and Objective: **The aim of this investigation to determine the range of morphological and ablative effects that can be achieved on dental enamel and dentin using ArF excimer laser irradiation at a wavelength of 193nm.**
Study Design/Materials and Methods: **Caries-free coronal enamel and dentin surfaces of 20 extracted human teeth were subjected to irradiation at 193nm using a Lamda-Physik model EMG 103 MSC and ArF fill. Morphology of cavity floors and walls were assessed by light microscopy and SEM.**
Results: **Morphological surface effects and ablation could be controlled effectively and reliably by choice of parameter combination, allowing the operator to achieve either a smooth, flat, or increasingly rough surface with differing degrees of selective ablation. No signs of thermal damage were apparent.**
Conclusion: **Excimer laser irradiation at 193nm provided clinically useful cavity preparations and surface morphological effects. Lasers Surg. Med. 20:142–148, 1997.**

Key words: dentin; enamel; excimer laser; morphology; tooth structure; tooth surface

INTRODUCTION

The use of lasers for ablation of hard dental tissues has been described by many authors using a wide range of lasers and parameters. Laser ablation effects on healthy [1,2] and carious enamel and dentin [3,4] have been investigated. Although side effects of laser ablation such as thermal and acoustic phenomena [4–12] continue to provide a challenge to researchers seeking clinical applications of these techniques, use of optimized wavelengths, pulse regimes, and delivery modes [12–15] are providing solutions to many of these issues. Several authors [15–22] have demonstrated minimal temperature increases and little or no structural damage to adjacent tissues during excimer laser ablation of enamel and dentin.

In progressing from basic ablation studies to consideration of clinical laser applications, it becomes important not only to consider ablation capability and side effects, but also to evaluate the residual dentin and enamel surfaces that can be achieved using laser irradiation. Surface morphology will directly affect the integrity and longevity of the tooth/restoration interface, which is closely related to the structural integrity of the restored tooth unit, the maintenance of pulpal health, and the long-term survival of the restoration.

This investigation was performed to determine the range of ablation and morphological effects that can be achieved on enamel and dentin surfaces using ArF excimer laser irradiation at 193nm.

MATERIALS AND METHODS

Sample Preparation

A total of 68 longitudinal sections, measuring ~1.5 mm in thickness, were prepared from

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the buccal, lingual, and proximal sections of crowns of caries-free human molar teeth, using a high speed diamond disc. Forty samples were prepared in enamel, 28 in dentin. Sample surfaces were polished flat using 3M Sof-Lex Pop-On Discs 1982C, 1982M, 1982F, and 1982SF. Sections were stored in distilled water with 0.01% w/v thymol at 3.3°C until use, when they were returned to room temperature over several hours.

Laser Device

A Lambda-Physik model EMG 103 MSC ArF excimer laser was used, emitting at a wavelength of 193 nm. Pulse duration measured 15 ns at a frequency of 10 Hz and spot size was set at 1.00 mm^2. Fluences ranged from 0.5–10 J/cm^2 and exposure times from 5–180 sec. The laser beam was reflected with a 193 nm coated reflector, with a transmitance of 5% at a 45° angle. Laser emission was measured with a Gentec Laser Power/Energy Monitor at the tooth surface.

Sample Irradiation

Four enamel and four dentin samples were irradiated at each parameter. The sections were clamped to a holder that could be adjusted in the X, Y and Z direction.

SEM Preparation

Upon completion of the irradiation procedures, the specimens underwent dehydration in a graded series of aqueous ethanol (30, 50, 70, 90, 100%) for 10 minutes at each concentration. Samples were mounted on stubs using colloidal silver liquid (Ted Pella, CA) and gold coated on a Pac-1 Pelco advanced coater 9500 (Ted Pella, CA). Scanning electron micrographs were taken on a Phillips 515 SEM (Mohawk, NJ).

Ablation Measurements

Crater dimensions were measured in the x and y plane from SEM micrographs. Crater depths were measured using interferometry techniques as described by Neev et al. [23].

RESULTS

Enamel

The effects achieved in enamel were directly related to the fluences and exposure durations applied. Crater sizes were documented in Table 1. An etched-looking crater margin 20–60 μm wide was observed in all samples (Fig. 1; see also Figs. 3,6). In the SEM, these marginal zones appeared roughened and bubbly, with partially dissolved enamel prisms sometimes protruding like an embankment from the irradiated surface (see Figs. 3,12). No areas of carbonization were visible to the naked eye or in the light microscope.

Table 1. Mean Ablation Measurements in Enamel

Fluence J/cm^2	Exposure time (s)	Depth (μm)	Length max. (μm)	Width min. (μm)	Sample No.
0.5	5	33	1,250 ± 40	320 ± 30	4
0.5	180	77	1,390 ± 30	290 ± 30	4
1.0	5	55	1,780 ± 60	450 ± 20	4
1.0	180	125	1,800 ± 40	490 ± 80	4
2.0	5	95	1,430 ± 40	420 ± 40	4
2.0	180	195	980 ± 40	250 ± 20	4
4.0	5	127	910 ± 60	390 ± 50	4
4.0	180	294	960 ± 40	250 ± 40	4
10.0	5	172	1,360 ± 40	450 ± 40	4
10.0	180	543	1,320 ± 40	470 ± 40	4

At low fluences (0.5J/cm^2), relatively small craters were produced in the enamel. After 5 s irradiation, only minimal ablation traces were visible (Fig. 1): longer irradiation durations produced increasingly larger and deeper craters. Irradiation durations of 30–180 s produced craters with very smooth floors and sides; as irradiation duration increased, the prismatic structure of the enamel became increasingly visible. No cracking, fissuring, or signs of melting were evident in any of the samples; occasionally a few small fragments of debris, 2–3 μm in diameter, were present. Similar results were obtained using a fluence of 1.0J/cm^2 (Fig. 2), although the craters produced were more marked than at 0.5J/cm^2. Crater floors and walls were extremely smooth, with no signs of laser damage such as cracking, pitting, melting, or crumbling.

At a fluence of 2.0–4.0J/cm^2, crater dimensions were greater than at lower fluences with corresponding irradiation durations. After 30 s laser exposure, the enamel crater floor showed some cracking toward the center of the samples, surrounded by an area of smoothly ablated dentin, with a peripheral zone at the crater edges that appeared rough and porous (Figs. 3,4). Results after 60s exposure were very similar, with perhaps somewhat smaller pores in the molten-looking crater margin zone, but with additional cracking and melting visible outside the crater margins. Irradiation durations of 180 s at both these fluences produced a smooth crater floor with very fine, evenly spaced pores, but with

Fig. 1. Enamel surface after 5 s irradiation at 0.5J/cm^2 (×50.5).

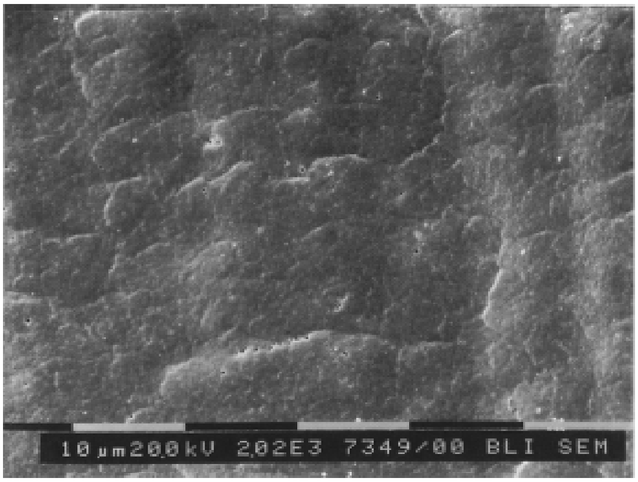

Fig. 2. Enamel surface after 30 s irradiation at 1.0J/cm^2 (×2020).

Fig. 3. Enamel surface after 30 s irradiation at 2.5J/cm^2 (×48.6).

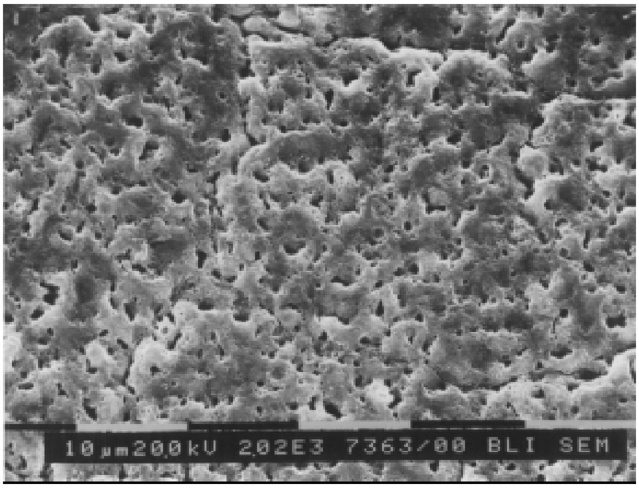

Fig. 4. Enamel surface after 30 s irradiation at 2.5J/cm^2 (×2020).

roughening and evidence of cracking and melting around the crater margins.

At a fluence of 10J/cm^2, irradiation for 5 s produced a shallow crater with a smooth floor with no cracks or signs of damage (Fig. 5). After 30 s, a superficial network of cracks was visible at the crater center (Fig. 6). Results after 60 s exposure were very similar, with a frosted zone of subablation laser effects again visible at the crater margin. After 180 s exposure, a clearly defined crater was again visible, with a smooth floor (Fig. 7).

Dentin

The effects achieved in dentin were also related to the fluences and exposure durations applied. Crater sizes in dentin are documented in Table 2. A roughened or etched-looking crater margin very variable in configuration was observed in all samples. In the SEM, these marginal zones appeared roughened and bubbly. No areas of carbonization were visible to the naked eye or in the light microscope.

Microstructural effects in dentin varied extensively, depending on fluence, exposure duration, and target position as related to the beam profile. Figure 8 depicts irradiation effects at 1J/cm^2 after 10 s at 10Hz. A sharp crater margin is not apparent; the dentin surfaces have a bubbly appearance on crater walls and floor; no open tubules are visible. Similar effects—shown at

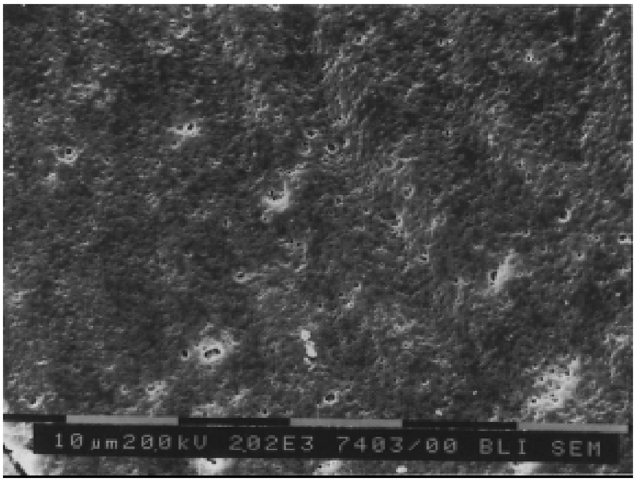

Fig. 5. Enamel surface after 5 s irradiation at 10.0J/cm^2 (×2020).

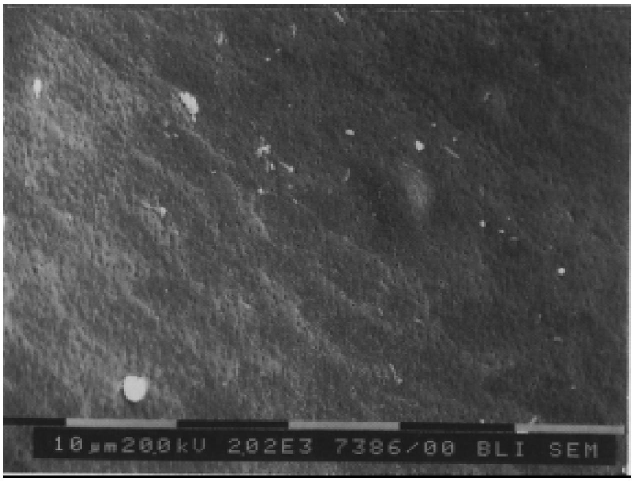

Fig. 7. Enamel surface after 180 s irradiation at 10.0J/cm^2 (×2020).

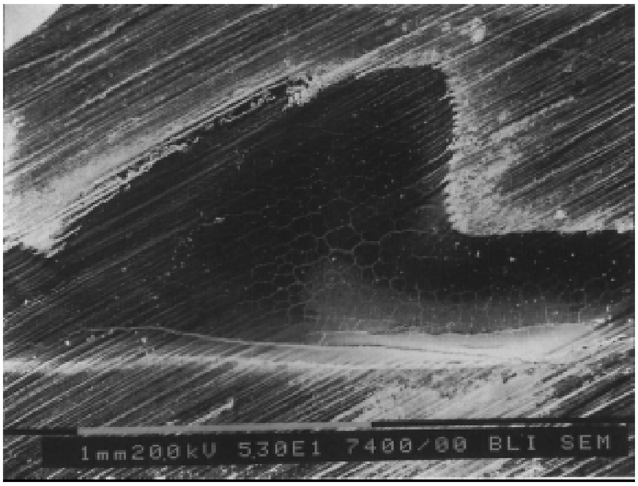

Fig. 6. Enamel surface after 30 s irradiation at 10.0J/cm^2 (×53).

higher magnification—were observed after 180 s irradiation at 1J/cm^2 (Fig. 9). However, irradiation at 1J/cm^2 for 60 s produced a crater with sealed dentin tubules on crater walls and floor and a smooth crater floor (Figs. 10,11). Figures 12 and 13 show the effects of irradiation at 2 J/cm^2 for 60 s: partially sealed dentin tubules in the crater wall, and open dentin tubules on the crater floor. The crater margin is not clearly defined, with lateral low-level irradiation effects visible for up to 300 µm. Sealed dentin tubules in the wall aspect, but a very porous crater floor was achieved at 2.5J/cm^2 after 90 s (Figs. 14,15); irradiation at 3 J/cm^2 for 30 s a smooth, glazed-looking crater floor (Fig. 16).

DISCUSSION

With increasing fluences and with longer exposure durations, ablation crater depth increased. Crater length and width did not, however, appear to increase at greater fluences and longer irradiation durations, although our sample number was too small for statistical analysis. Crater depth is related to the amount of energy applied at one location, whereas crater width and length are to a large extent determined by the shape of the focused area of laser radiation and the energy distribution within the beam profile. Similar effects were described by other authors [12,17,21].

The etched-looking crater marginal zone seen in all of the samples irradiated in this investigation was somewhat narrower and less white in appearance in samples irradiated for a short time at low fluences than in samples irradiated extensively at higher fluences. Its presence was attributed to the cumulative effects of marginal irradiation at the outer edges of the beam profile, which sufficed to alter the enamel or dentin surface, but remained below the ablation threshold.

Smooth and clean cavity surfaces were achieved consistently in enamel using a low fluence of 0.5–1.0J/cm^2, irrespective of irradiation duration. At higher fluences, smooth enamel surfaces were also achieved, especially after shorter irradiation durations. These findings are consistent with the ablation studies published by Feuerstein et al. [19] and Arima et al. [12], who achieved smooth surfaces in enamel at lower energy densities and rougher crater floors at higher energy densities. At the parameters found to pro-

Table 2. Mean Ablation Measurements in Dentin

Fluence J/cm^2	Exposure Time (s)	Depth (μm)	Length max. (μm)	Width min. (μm)	Sample No.
1.0	10	42	1,800 ± 30	650 ± 40	4
1.0	60	186	2,200 ± 60	970 ± 80	4
1.0	180	233	1,900 ± 40	800 ± 30	4
2.0	60	206	1,600 ± 20	470 ± 20	4
2.5	10	51	1,850 ± 30	500 ± 20	4
2.5	90	77	2,000 ± 40	450 ± 60	4
3.0	180	105	2,300 ± 60	1,100 ± 40	4

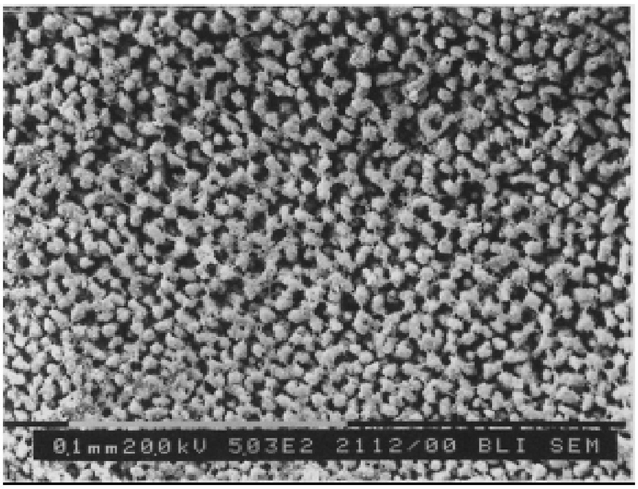

Fig. 8. Dentin surface after 10 s irradiation at 1.0J/cm^2 (×503).

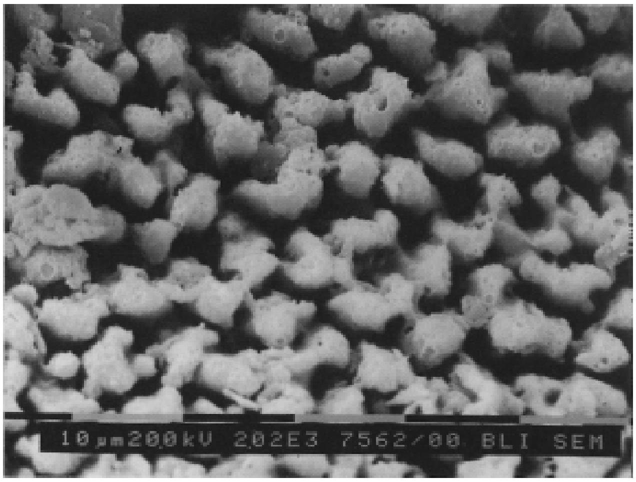

Fig. 9. Dentin surface after 180 s irradiation at 1.0J/cm^2 (×2020).

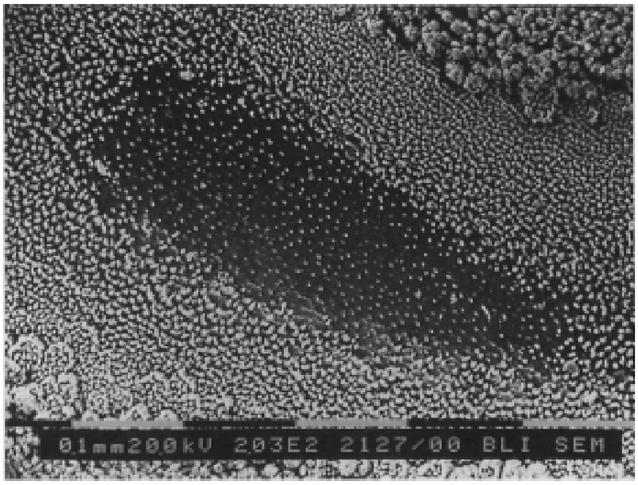

Fig. 10. Dentin surface after 60 s irradiation at 1.0J/cm^2 (×203).

duce a smooth residual enamel surface, thermal effects should be very low according to work published by Neev et al. [16] and Frentzen and Koort [17]. Thus use of the ArF laser at appropriate parameters is clinically feasible and should achieve good results.

In dentin, a wide range of effects was documented in this investigation. Surface effects ranging from sealing of dentinal tubules to microroughening were achieved. Clinically, these results are significant, because they indicate that this wavelength can be used to achieve the different surface morphologies required for restorative purposes. For example, smooth walls and floors are often indicated when working with restorative materials such as amalgam, cast metals, or ceramics. However, adhesive techniques involving resins require microrough surfaces so that micromechanical interlocking can function as a retentive mechanism. Sealing of dentinal tubules is desirable in many clinical situations, providing a barrier, e.g., to the penetration of pathological factors along tubular structures. Such a sealing process also may be significant in the treatment of dentinal sensitivity, as proposed by Neev et al. [16]. As these effects can be achieved with minimal intradentinal temperature rises [16,17], use of excimer laser irradiation at 193nm on dental hard tissues should be safe and effective in the clinical situation.

The effects of irradiation varied considerably between the margin and the center of the irradiation spot due to the inhomogeneous delivery of energy by the laser beam. Thus if this laser device is to be applied clinically, a reproducible and constant beam profile is required in order to achieve predictable and homogeneous effects. Moreover, a flexible delivery system suitable for dental pur-

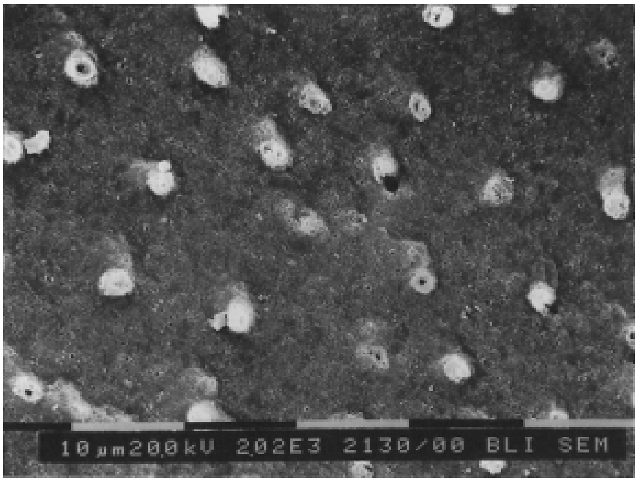

Fig. 11. Dentin surface after 60 s irradiation at 1.0J/cm² (×2020).

Fig. 12. Dentin surface after 60 s irradiation at 2.0J/cm² (×203).

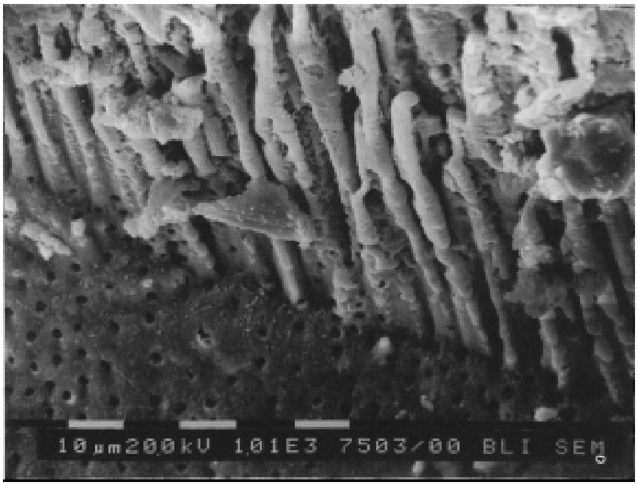

Fig. 13. Dentin surface after 60 s irradiation at 2.0J/cm² (×1010).

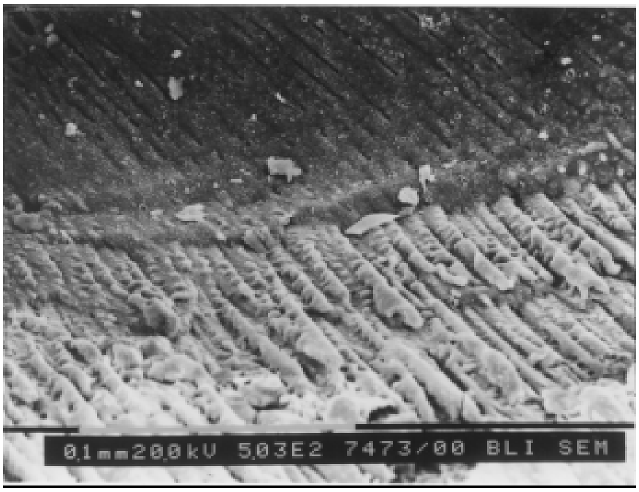

Fig. 14. Dentin surface after 90 s irradiation at 2.5J/cm² (×503).

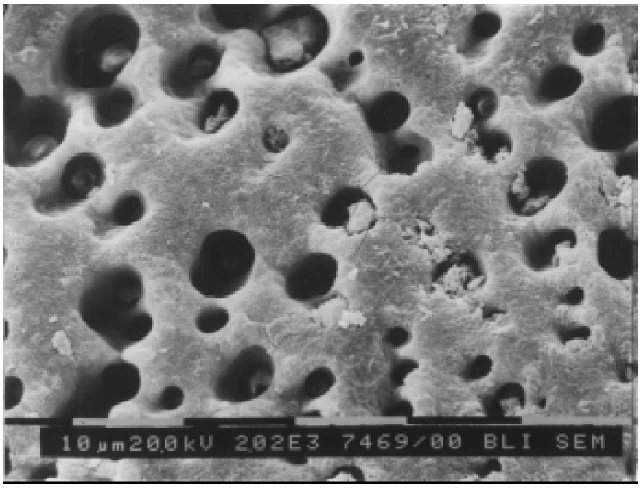

Fig. 15. Dentin surface after 90 s irradiation at 2.5J/cm² (×2020).

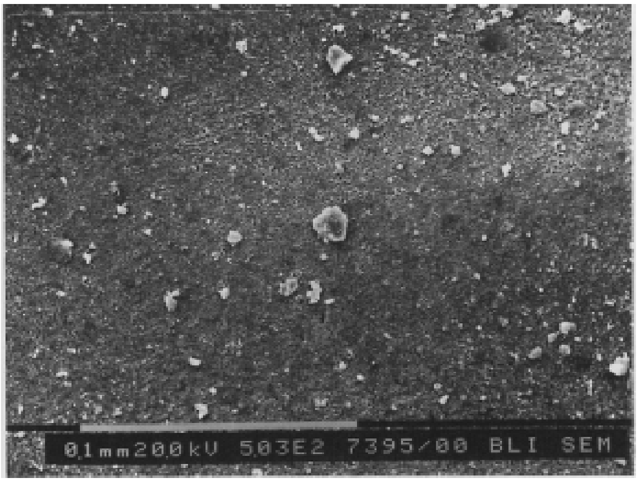

Fig. 16. Dentin surface after 30 s irradiation at 3.0J/cm² (×503).

poses is necessary. If these requirements can be fulfilled, the excimer laser emitting at 193nm will constitute an effective and useful tool for the ablation and surface modification of hard dental tissues.

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